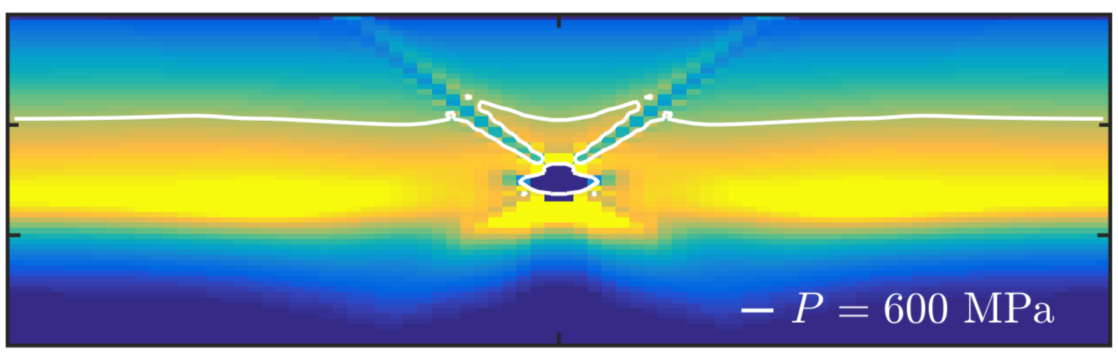
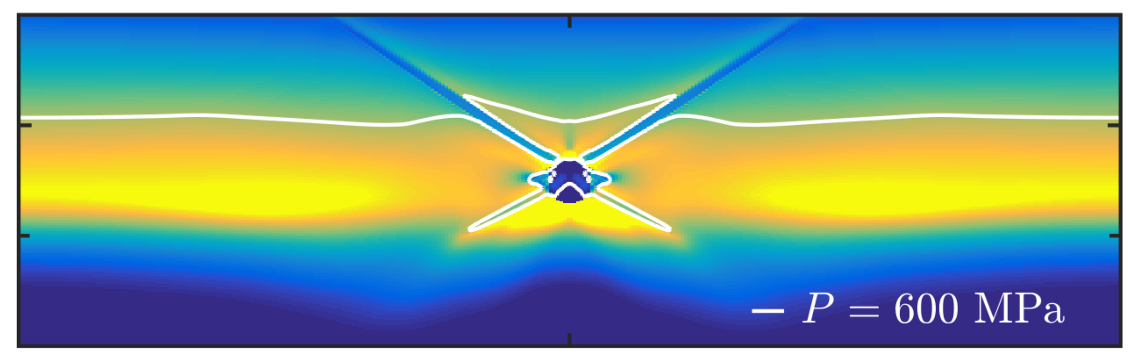
Numerical modelling of (lithospheric) deformations with frictional plasticity

T. Duretz, R. de Borst, L. Räss, P. Yamato,
T. Hageman, L. Le Pourhiet





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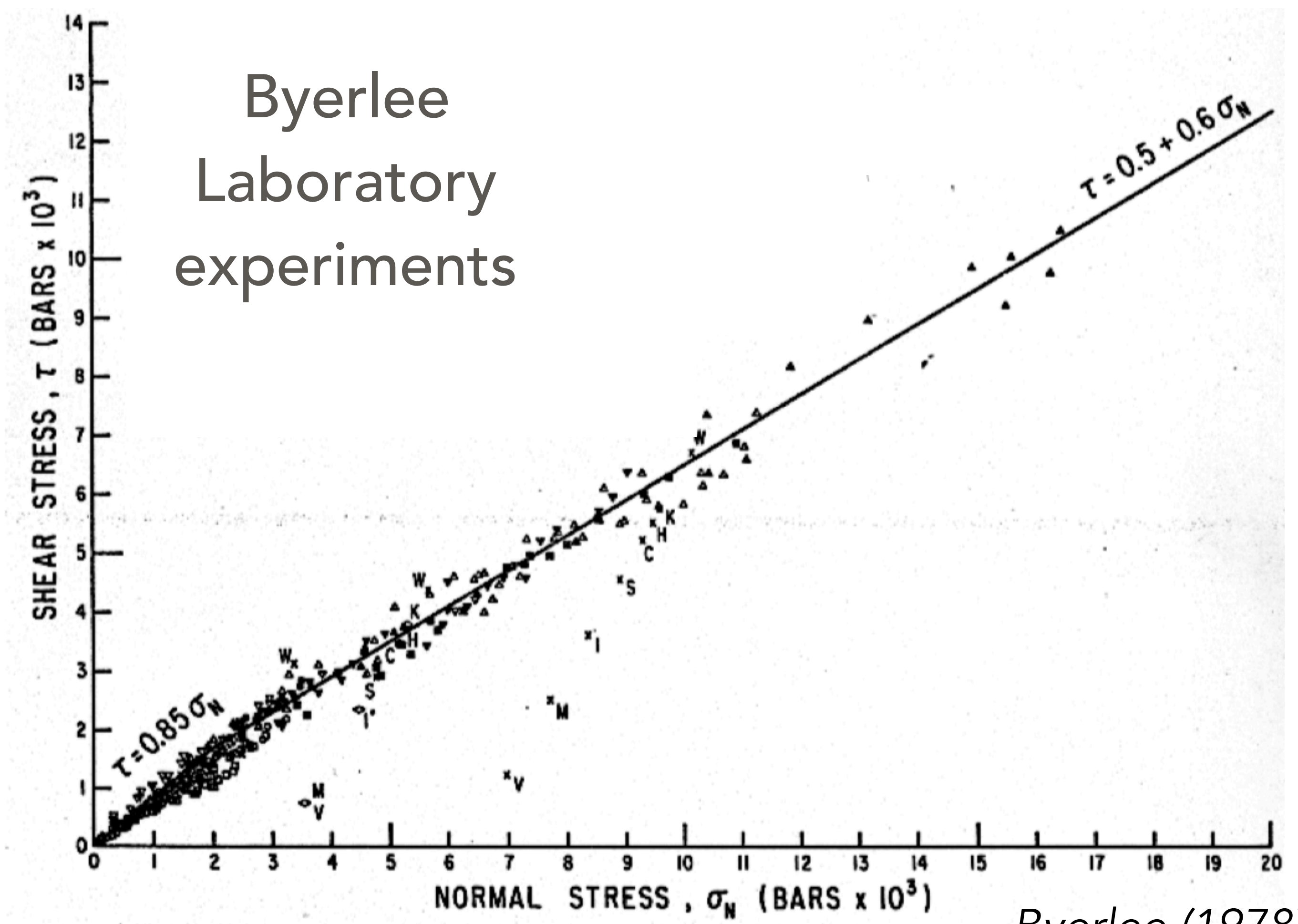
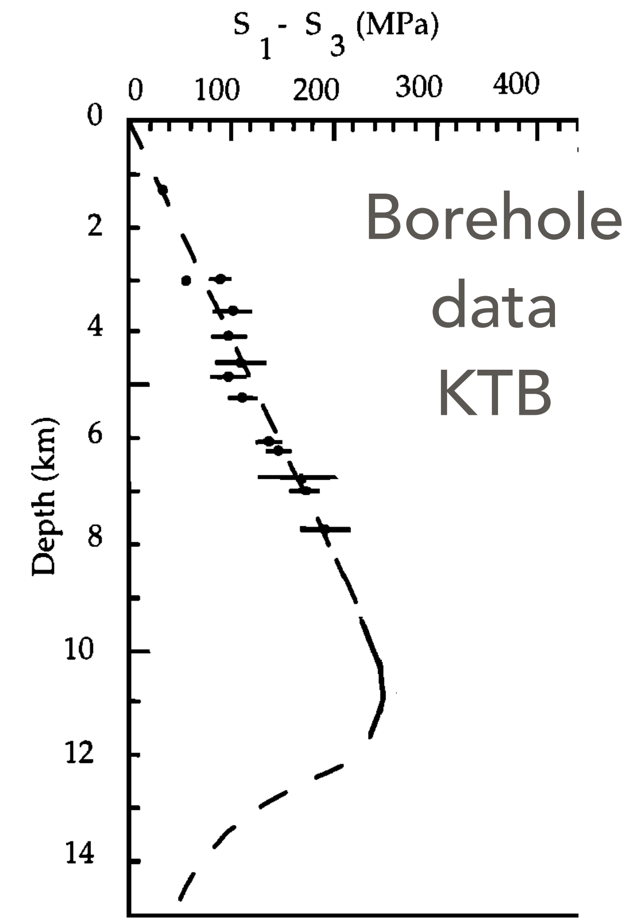
Rock mechanics



Byerlee (1978)



Zoback & Harjes (1997)

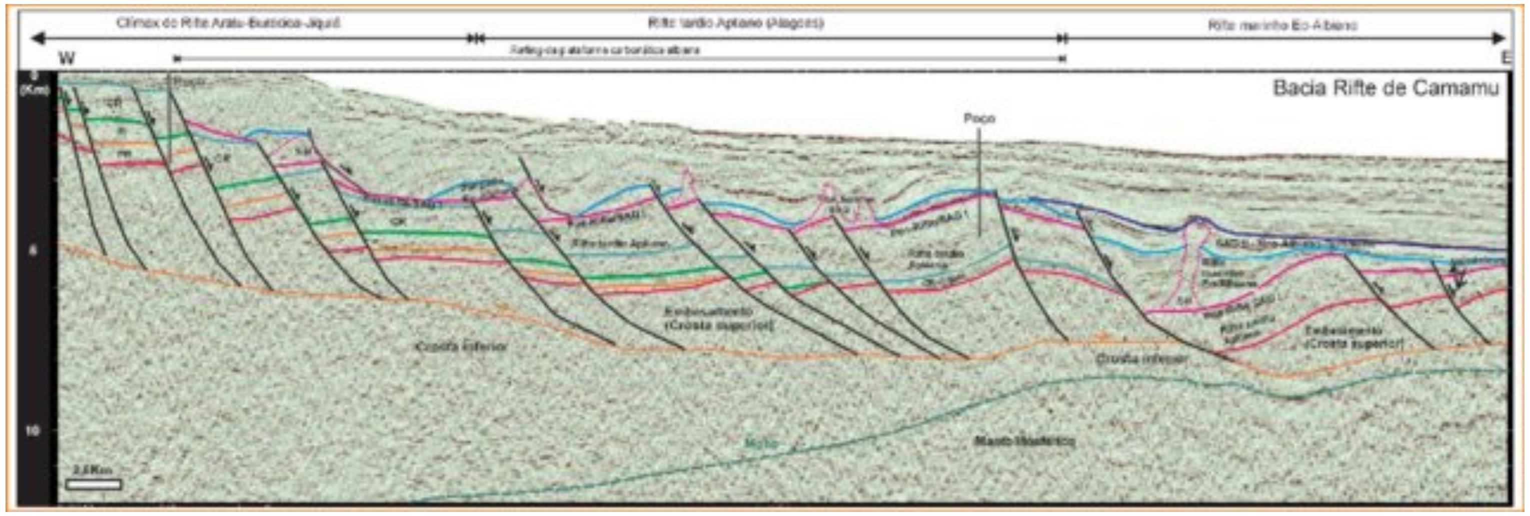
Yield stress increases with pressure: *Frictional plasticity*

The static coefficient of friction of ~30°

Almost independent on the rock type

Geological observations

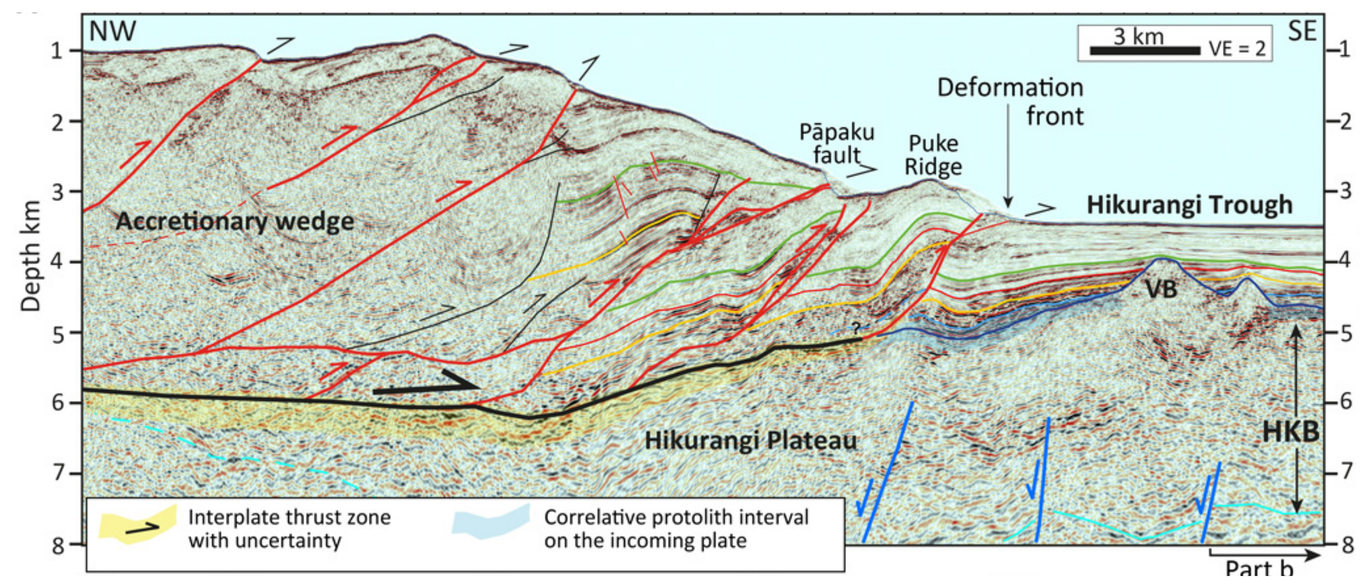
Camamu basin — Brazilian margin (Ferreira, 2018)



Fault angles depend on

tectonic setting / loading type

Hikurangi margin — New Zealand (Barnes et al., 2020)



Faults are essential in Earth sciences:

Structure of the crust, fluid and mass transfers, seismogenesis…

The ability to predict fault-like zones development is necessary

Geodynamic models and plasticity

Geodynamic models are continuous and have limited resolution

Frequent assumptions of geodynamic models:

Incompressibility, no elasticity, lithostatic pressure, local/rate-independent plasticity

↓

No feedback of plasticity on pressure

Geodynamic models and plasticity

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↓

No possibility to build-up
and resolve shear band propagation

Geodynamic models and plasticity

Geodynamic models are continuous and have limited resolution

Frequent assumptions of geodynamic models:

Incompressibility, no elasticity, lithostatic pressure, local/rate-independent plasticity

Fixed 45°
shear band angle

Not Mohr-Coulomb
nor Drucker-Prager

Geodynamic models and plasticity

Geodynamic models are <u>continuous</u> and have <u>limited resolution</u>

Frequent <u>assumptions</u> of geodynamic models:

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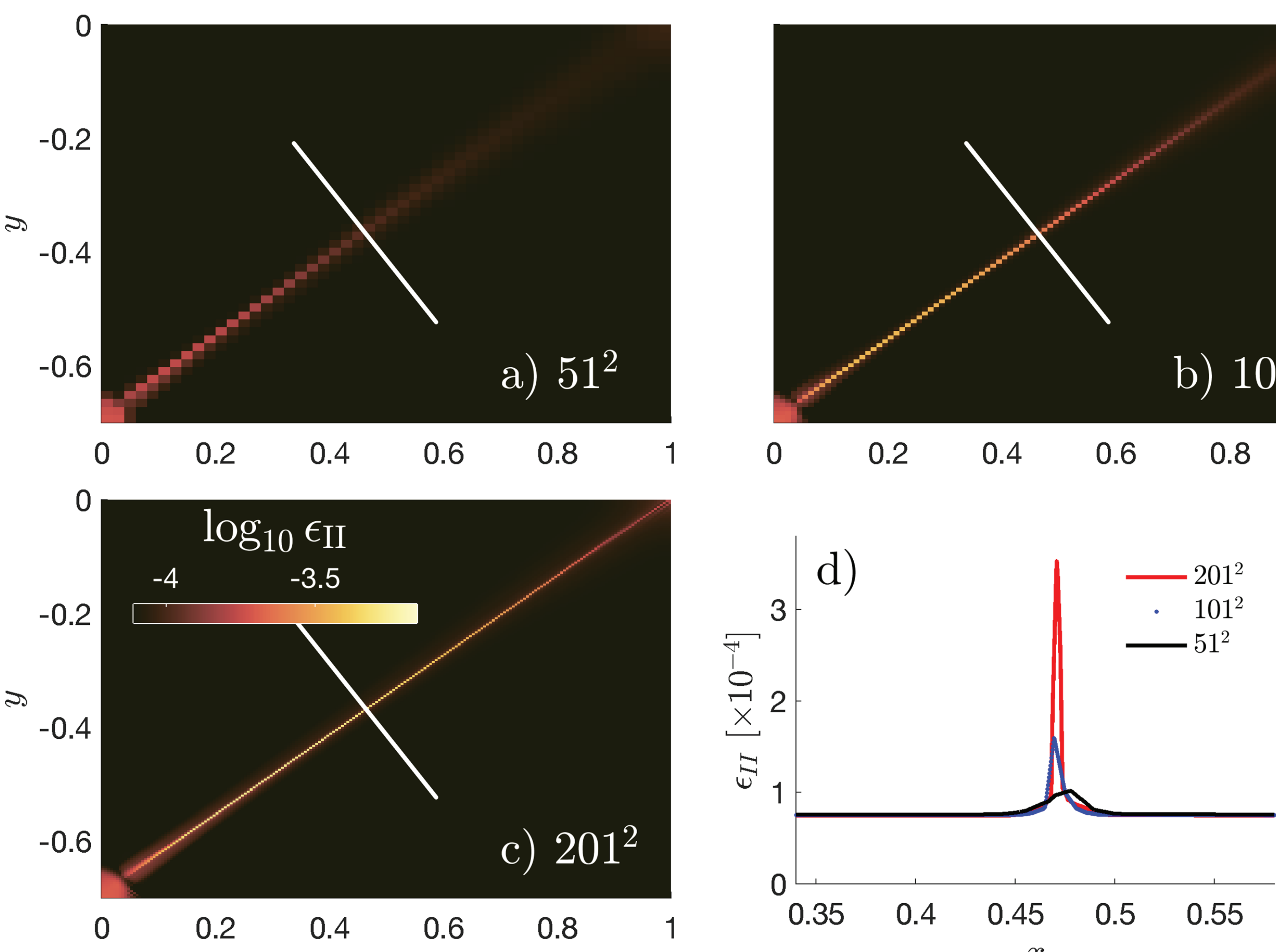
Mesh dependence
and lack of convergence



Duretz et al., (2019)

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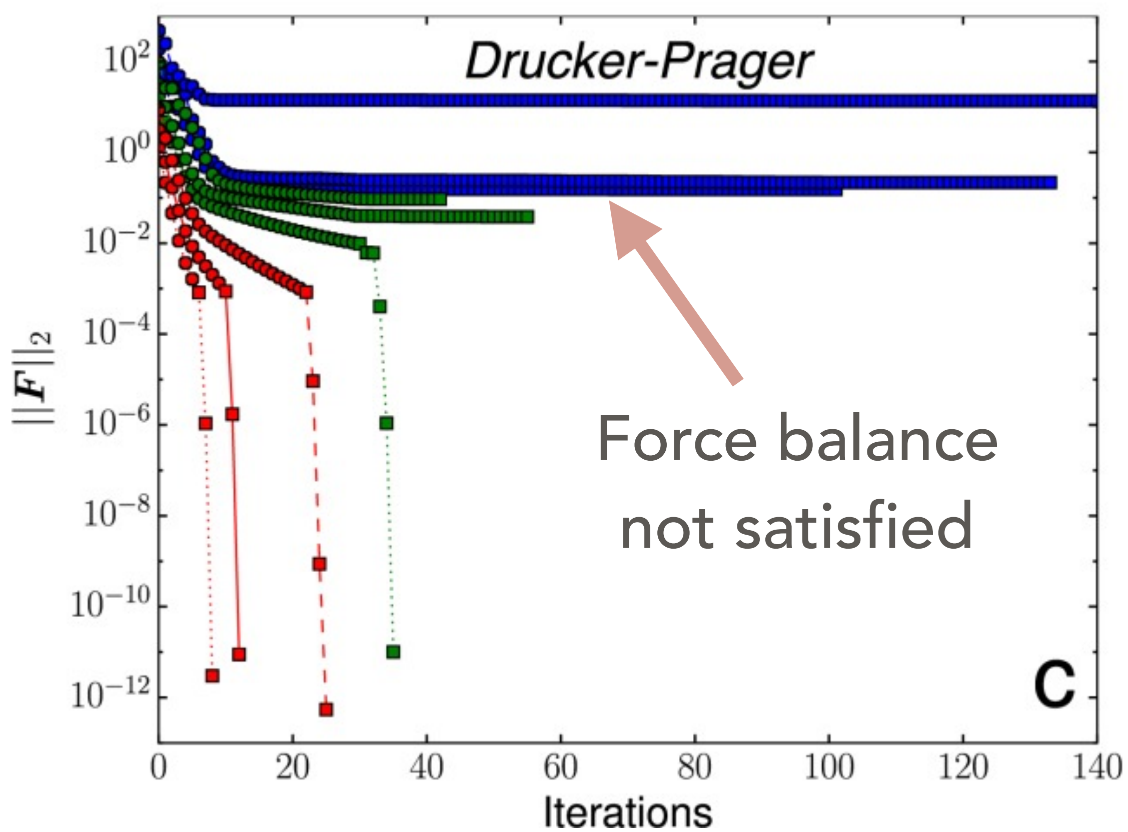


Speigelmann et al., (2016)

Geodynamic models and plasticity

Geodynamic models are continuous and have limited resolution

Frequent assumptions of geodynamic models:

Incompressibility, no elasticity, lithostatic pressure, local/rate-independent plasticity

Not supported by lab. data nor observations

Mesh dependence and lack of convergence

What can we do?

Regularisation

Drucker-Prager plasticity: $$F = \tau_{II} - c\cos\phi - p\sin\phi = 0$$

No time nor length-scale

Rate-dependent viscoplasticity: $$F = \tau_{II} - c\cos\phi - p\sin\phi - \eta^{\mathrm{vp}}\dot{\lambda}$$

Overstress

temporal regularisation

“local”

Straightforward implementation
In existing codes

Gradient-based regularisation: $$F = \tau_{II} - c\cos\phi - p\sin\phi + \gamma\Delta\epsilon^{\mathrm{p}}$$

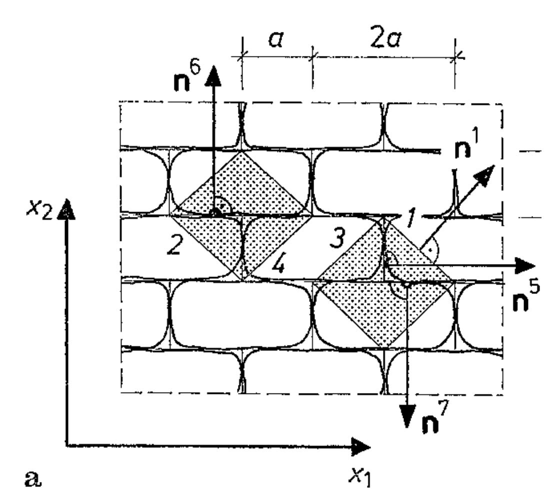
spatial regularisation

+ 1 dof

Cosserat medium: $$F = \tau_{II} - c\cos\phi - p\sin\phi$$

spatial regularisation

+ 1 dof in 2D



Mühlhaus (1989)

Implementation

<u>Ideally, for a fair comparison we need all in a single code</u>

Finite differences/staggered grid

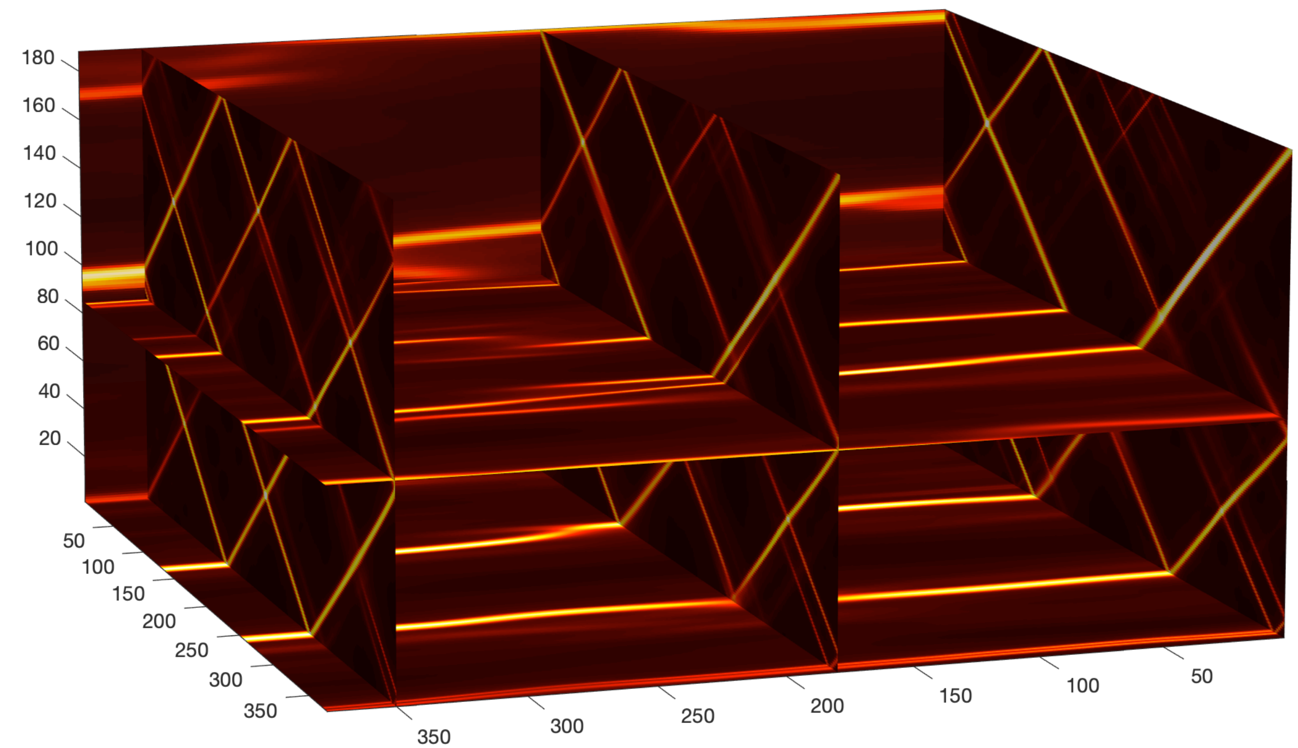
~~Full Newton + Line searching~~

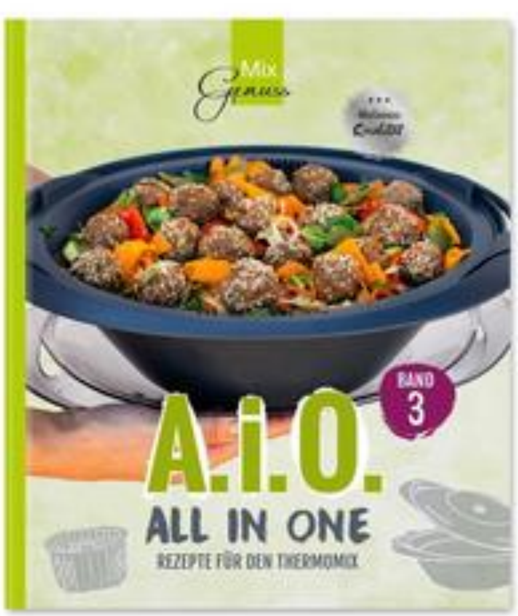
~~Direct iterative solver~~

~~Modified Powell-Hestenes~~

~~(Cholesky factors of symmetrised Jacobian)~~

Open source julia routines





Fully iterative accelerated **pseudo-transient** integration

<u>All-in-one approach</u>: combined linear/non-linear solve

ParallelStencil.jl package - multiple **GPUs**

Simple path to 3D

Implementation

Ideally, for a fair comparison we need all in a single code

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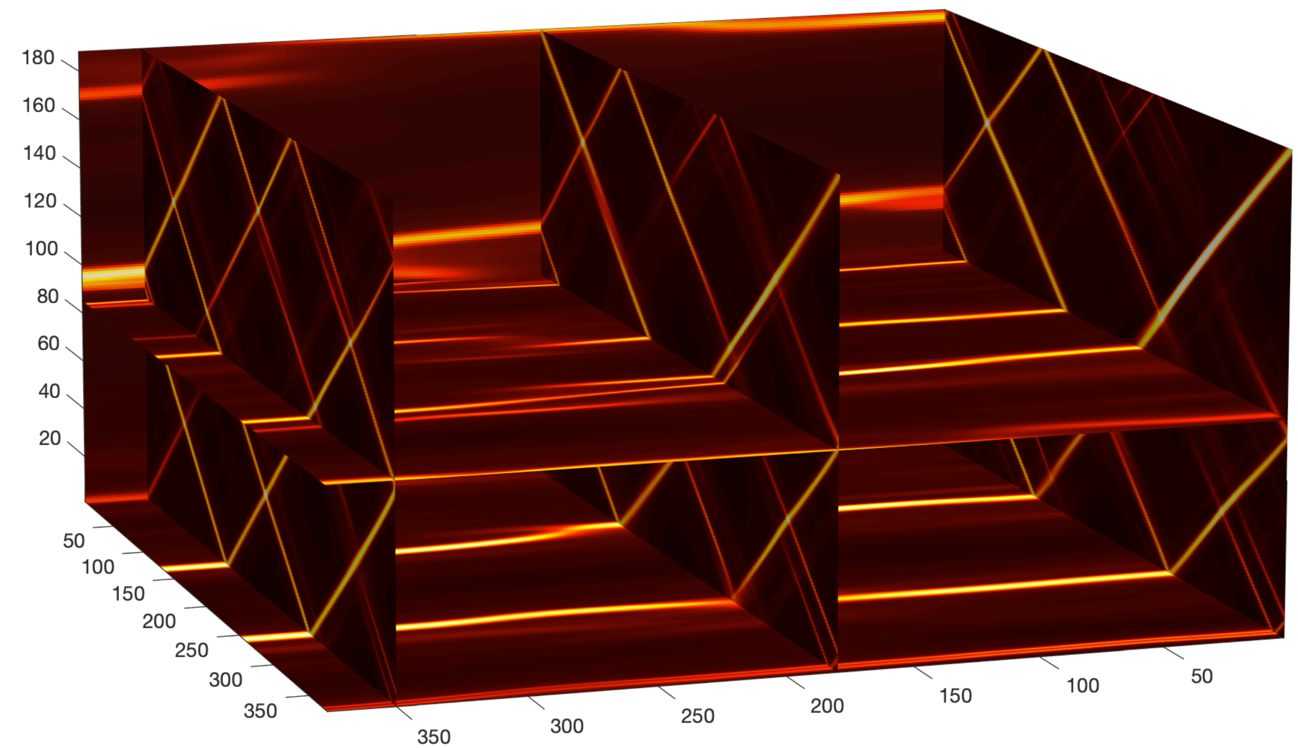


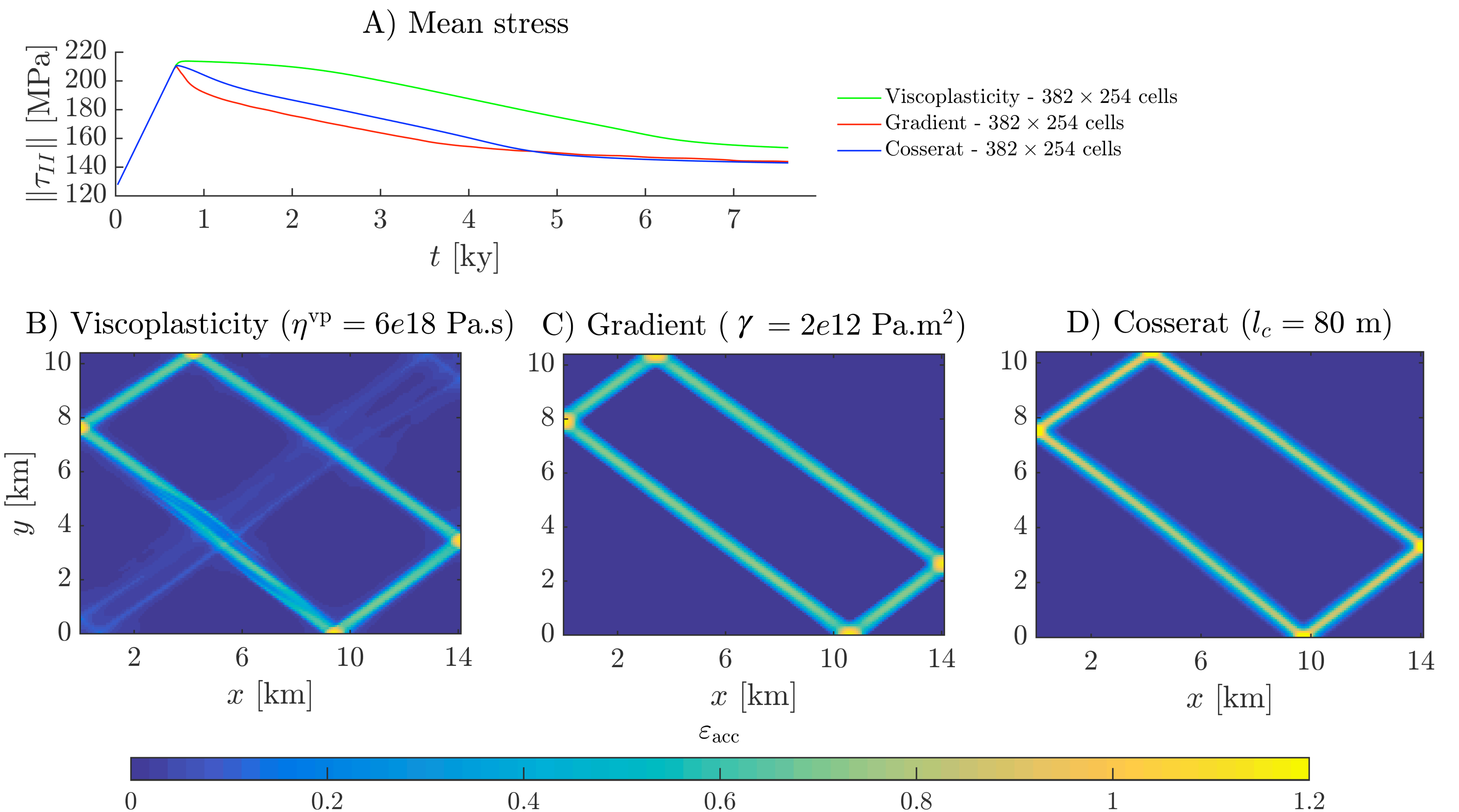
EGU22-9815 | Presentations | GD9.1

Assessing the robustness and scalability of the accelerated pseudo-transient method towards exascale computing

Ivan Utkin, Ludovic Rass, Thibault Duretz, Samuel Omlin, and Yury Podladchikov

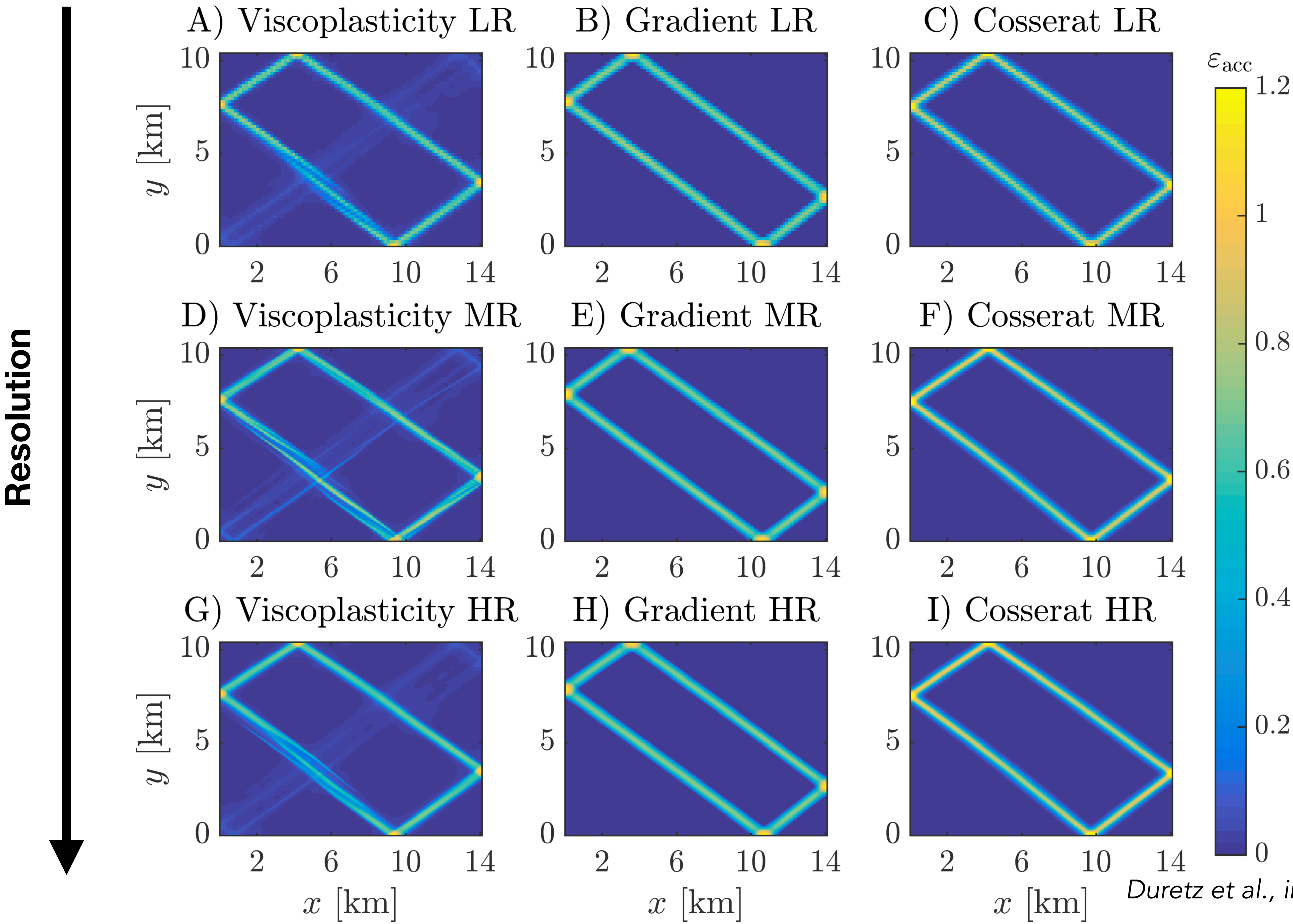
Thu, 26 May, 17:26–17:33 Room -2.47/48 **Tomorrow!**

Different regularisations: Shear bands



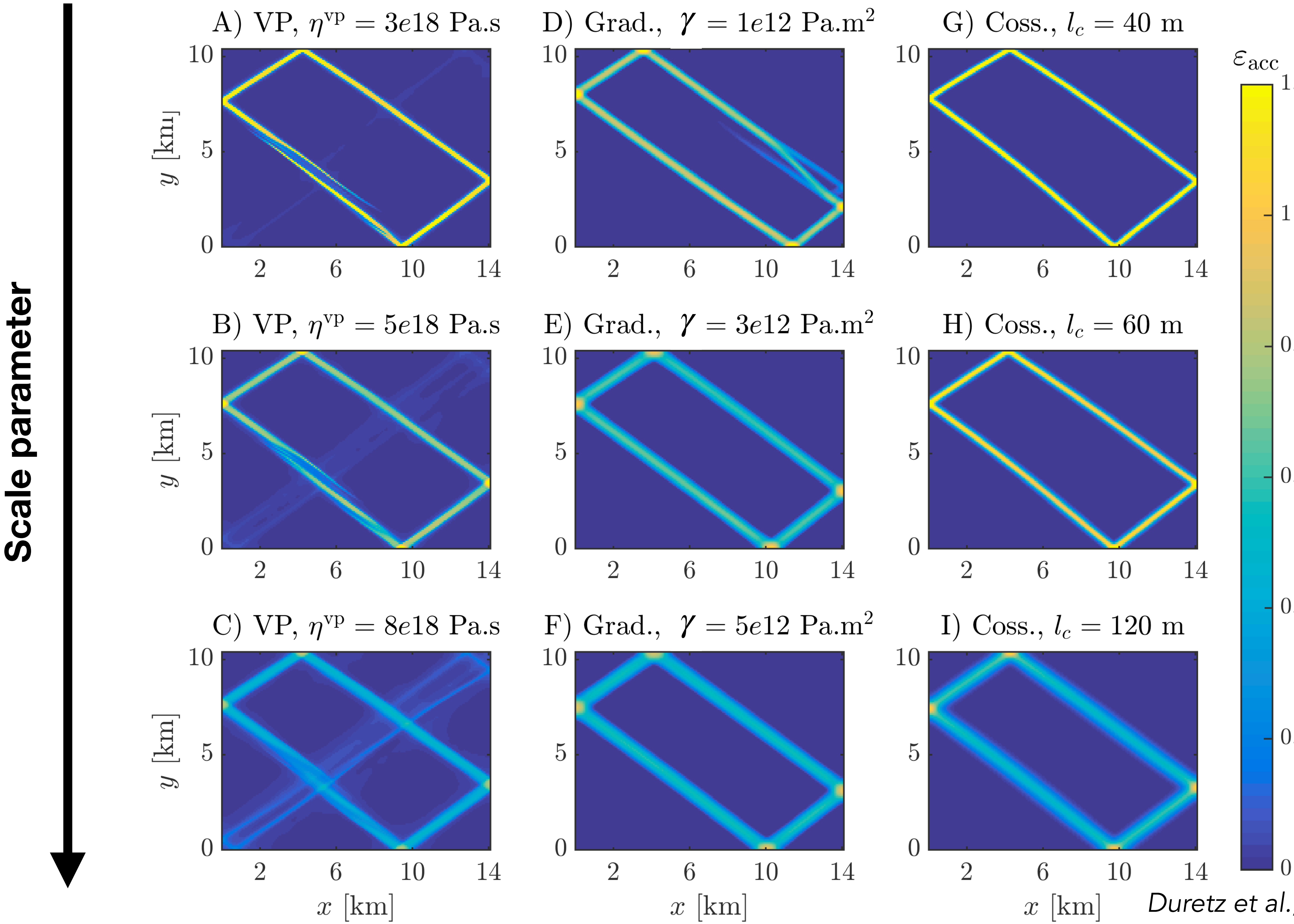
Duretz et al., in prep

Regularisations: Resolution



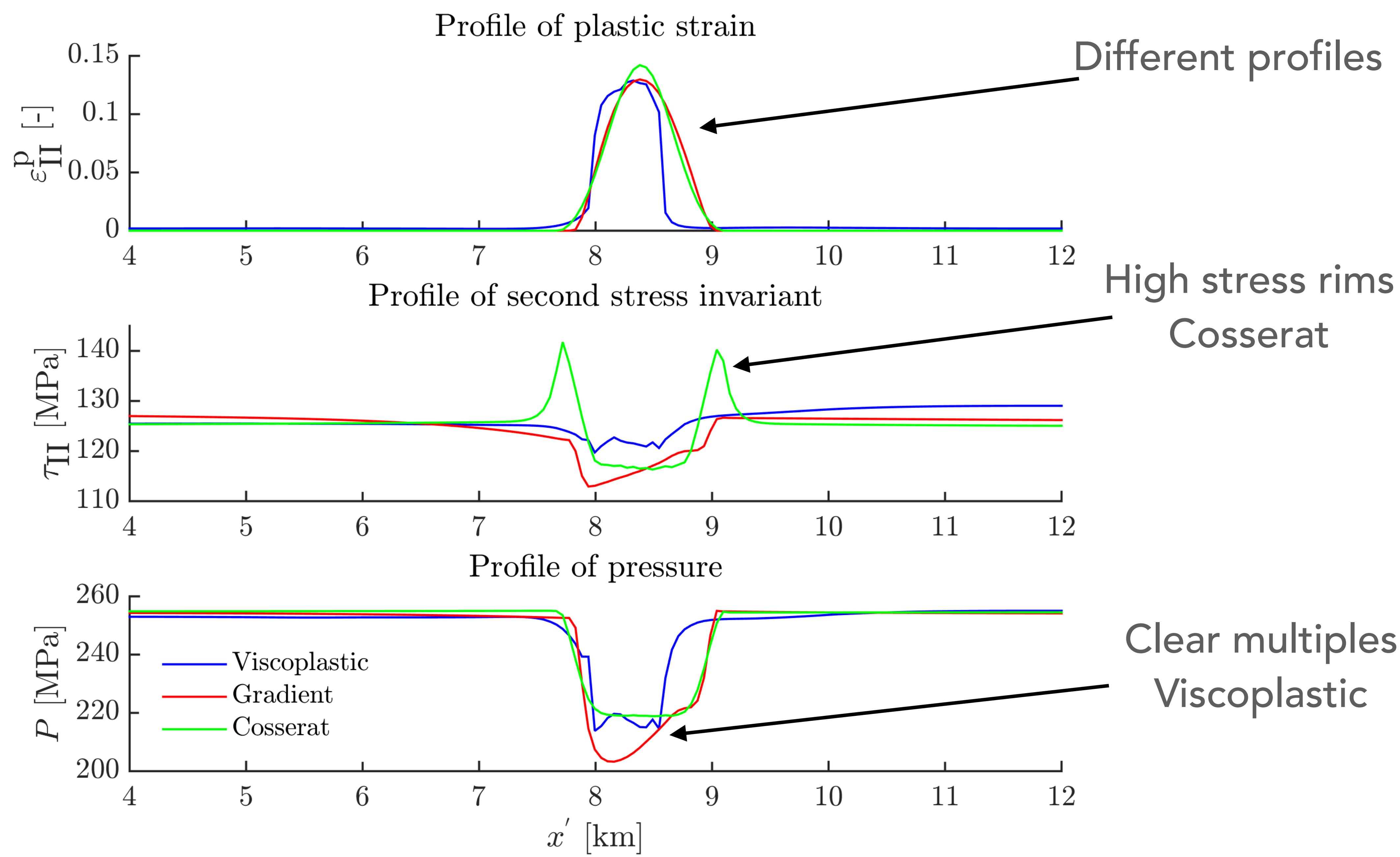
Duretz et al., in prep

Regularisations: Parameters



Duretz et al., in prep

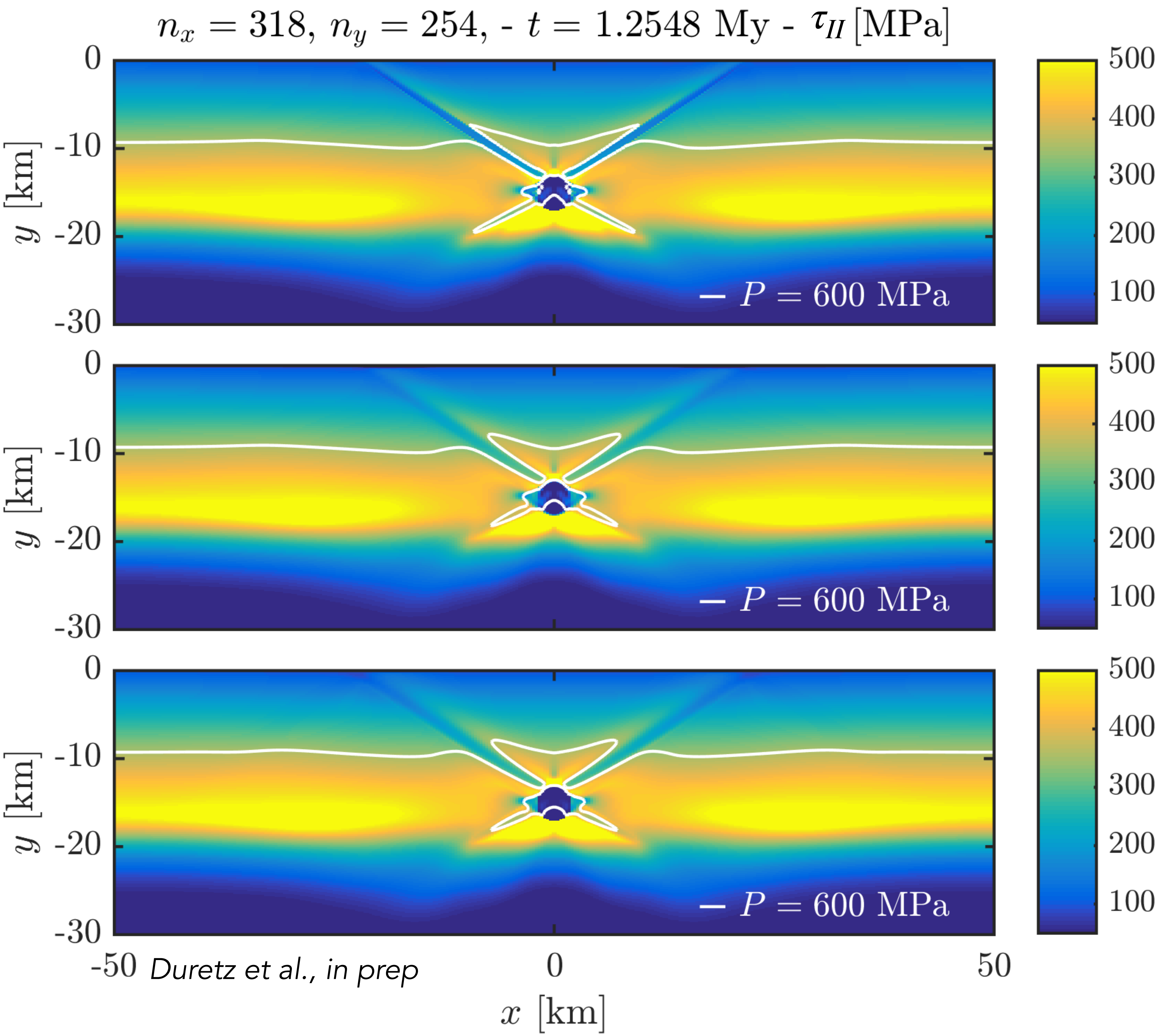
Different regularisations: Shear bands



Duretz et al., in prep

Some interesting differences in shear band properties

Different regularisations: Crust



Duretz et al., in prep

Viscoplastic
$\eta = 10^{21}$ Pa.s

Viscoplastic + gradient
$\eta = 10^{21}$ Pa.s
$\gamma = 2.5 \times 10^{13}$ Pa.m^2

Viscoplastic + Cosserat
$\eta = 10^{21}$ Pa.s
$l_c = 200$ m

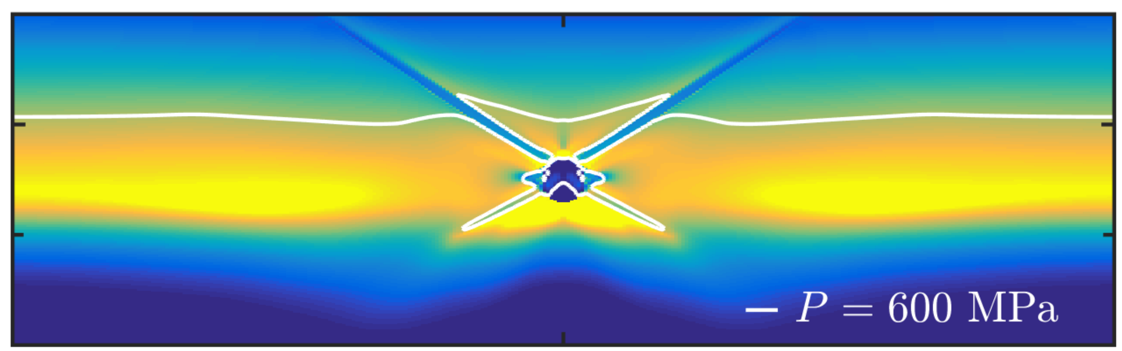
Conclusions

Frictional plasticity is a long-lasting problem is geodynamic modeling

Some simple solutions exists and others have to be explored

Viscoplastic formulations are straightforward and efficient

Can be readily used in geodynamic simulations



…however a proper length-scale would also be welcome

Likely a combination of gradient/Cosserat with viscoplasticty

would be even better suited